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Inventors: Paul M. Reepschlager and Patrick Pilot

Title: Automatic Raman Gain Control

Docket No: 3650-0011US

AFFIDAVIT UNDER 37 C.F.R. 1.131

We, Paul M. Reepschlager and Patrick Pilot of Ottawa, Ontario, Canada hereby make oath and say as follows:

(1) THAT the attached "Invention Disclosure Submission Reply" and "Invention Disclosure In Rough" mentioned therein and attached hereto were produced before the filing date (January 26, 2001) of published United States Patent Application No. 09/769,522 (which has no domestic priority) and before the filing date (January 30, 2001) of published United States Patent Application No. 09/772,489.

(2) THAT the subject matter of the instant application (United States Patent Application No. 09/824,798 was conceived before the filing date (January 26, 2001) of published United States Patent Application No. 09/769,522 (which has no domestic priority) and before the filing date (January 30, 2001) of published United States Patent Application No. 09/772,489.

EXECUTED at Ottawa, Ontario, Canada

this 9 day of October, 2003.

Paul M. Reepschlager
MM

SWORN BEFORE ME at the City of Ottawa

in the Regional Municipality of Ottawa-Carleton

this 9th day of October, 2003.

Commissioner for Oaths
or Notary Public

EXECUTED at Ottawa, Ontario, Canada

this 2nd day of October, 2003.

Patrick Pilot

SWORN BEFORE ME at the City of Ottawa

in the Regional Municipality of Ottawa-Carleton

this 2nd day of October, 2003.

Commissioner for Oaths
or Notary Public

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Invention Disclosure Submission Reply

I P LAW GROUP
OTTAWA DOCKET DEPT.

Disc No:		Received Date:	
Disclosure Title:	Automatic Raman Gain Control		

ORIGINAL
DO NOT MARK

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13688RO

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---=== Attachments ===---

File Name	File Type	File Comments
AutoRamanGainPatent.doc	Microsoft Word (*.doc)	Invention disclosure in rough.

<End of Attachments>

Were there additional inventors involved:	yes	Was there contractor involvement:	no
Name of Supervisor or Divisional Head:		Name of VP:	
MARC VEILLEUX			
LOB:	SP&C	Business Unit:	Other (SP&C)
Conception Date:			
Has this invention been discussed with others? If so, please complete:			

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Inside Nortel - Whom?	DAVE PARK, 1U20-M	Outside Nortel - Whom?	
Inside Nortel - When?		Outside Nortel - When?	
NDA?	no		

Are you aware of any imminent future disclosures? Please provide dates and details:

No

Keywords for Searching:	Products that will use this invention:

Does this invention arise from any arrangement involving an external organization? no

Is this invention relevant to a Standards Activity?	Internal Funding Project #'s:
no	251-25994

Technical Information

Brief Description of the Invention:

BackgroundA vehicle for obtaining additional optical gain in an amplified fiber optic span is found in pumping the line fiber with high-energy photon (low wavelength) lasers. In this ?Raman effect?, high-energy photons are absorbed by the fiber and may be re-emitted in the form of stimulated emission in the presence of longer wavelength photons, thus resulting in amplification. The gain profile for the stimulated re-transmission has a finite width. Signal gain across a wide spectral profile may involve the superposition of gain profiles for several Raman pumps. Using adequate pump wavelengths to provide gain across a signal band, a model can be derived to predict the relative pump powers to achieve a desired gain profile through pump gain profile superposition, while taking into account several secondary non-linear fiber optic effects as well. A closed loop control strategy is required to ensure that gain inaccuracies induced by the application of such a complex model are corrected.Invention:A closed loop gain control strategy for Raman amplifcation using system wavelength profile information is proposed.

Problem Solved by the Invention:

This invention corrects for open loop gain implementation, wherein Raman gain is estimated on the basis of a modeled solution and the resulting gain profile is not corrected. The method proposed to be implemented in the field permits corrections due to Raman gain model imperfections.

Solutions that have been tried and why they didn't work:

Prior solution: A closed loop system which monitors system span profile parameters for gain derivation, but does not take into account the dynamic nature of these system profiles. Under such a proposal, the gain control algorithm would fail. This method proposes a solution for permitting dynamic adjustments to system parameters, thus permitting an accurate derivation of the Raman Gain.

Specific elements or steps that solved the problem and how they do it:

See the attachment

Commercial value of the invention to Nortel and Nortel's major competitors:

Raman amplification is a new technology implemented in Optical amplifier networks, and is necessary for growth of bandwidth. The implementation of this technology under tightly controlled conditions has only recently been made possible through the use of relatively inexpensive Optical Spectrum Analyzers in the network. The patent for the gain control stategy has merit in preventing other competitors from using Nortel IP in their systems. Since the technology is new (and hot), it is critical patent this idea to protect Nortel's market interests.

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13688RO Attachment

Automatic Distributed Raman Amplifier Gain Control

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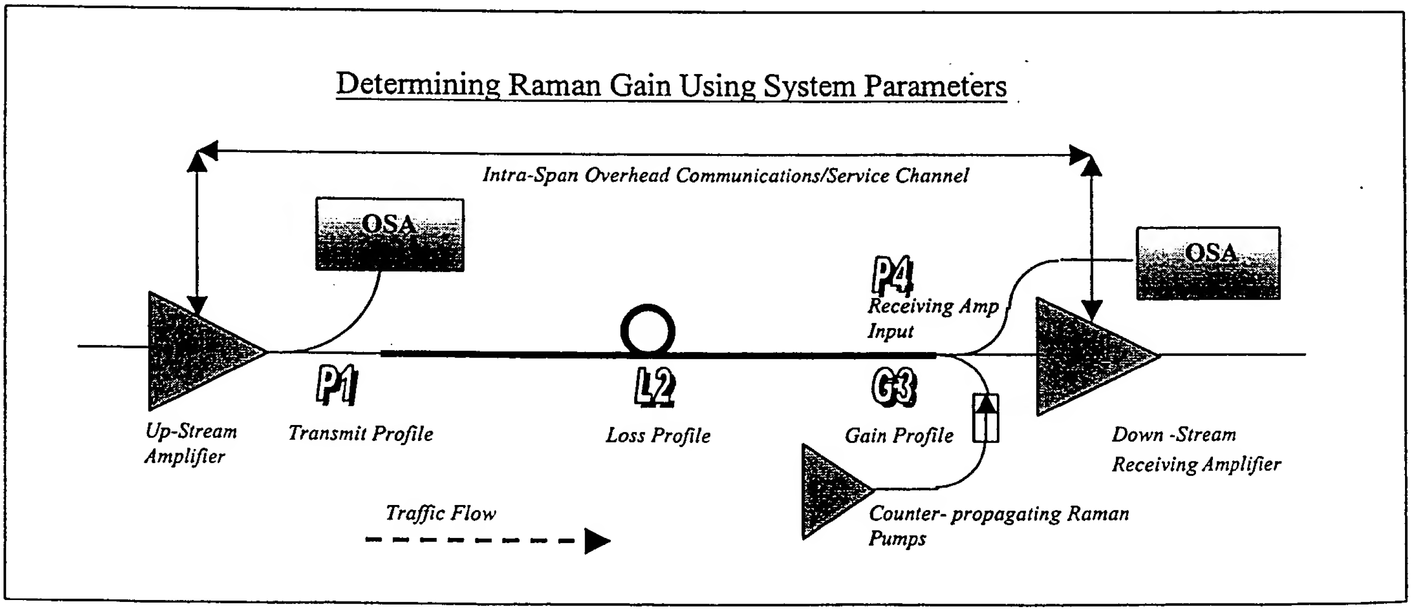
Background: Raman Amplification

A vehicle for obtaining additional optical gain in an amplified fiber optic span is found in pumping the line fiber with high-energy photon (low wavelength) lasers. In this "Raman effect", high-energy photons are absorbed by the fiber and may be re-emitted in the form of stimulated emission in the presence of longer wavelength photons, thus resulting in amplification. The gain profile for the stimulated re-transmission has a finite width. Signal gain across a wide spectral profile may involve the superposition of gain profiles for several Raman pumps. Using adequate pump wavelengths to provide gain across a signal band, a model can be derived to predict the relative pump powers to achieve a desired gain profile through pump gain profile superposition, while taking into account several secondary non-linear fiber optic effects as well. A closed loop control strategy is required to ensure that gain inaccuracies induced by the application of such a complex model are corrected.

The Invention: Automatic Raman Gain Control

The inclusion of cost effective optical spectrum analyzers (OSA) to monitor wavelength profiles has permitted the mapping of transmit and receive profiles within a span. If collected in a central location (say at the receiver) this mapping information can be utilized to derive the Raman gain within the span. Consider the diagram below.

Determining Raman Gain Using System Parameters



Having knowledge of the following information:

- the up-stream transmit amplifier originating profile (P1),

- the Span loss profile (L2),
- and the profile measured at the input to the receiving amplifier (P4),

the Raman gain spectral contribution (G3) incident on the receiving amplifier can be determined:

$$P4(\lambda) = P1(\lambda) + G3(\lambda) - L2(\lambda), or$$
$$G3(\lambda) = P4(\lambda) - P1(\lambda) + L2(\lambda)$$

Calculation of G3 would preferably be performed at the receiving end.
In this method the gain and ripple in the Raman gain profile will both be directly mapped as opposed to estimated through reliance on model equations. Measurement of an actual spectral profile at the receiving amplifier permits pre-compensation of the Raman gain profile to be implemented and tracked with a high level of confidence.

Some level of inaccuracy is to be expected in the derived Raman Gain profile. This inaccuracy will be manifested in OSNR (optical signal to noise ratio) results. Thus, as an outside loop in the control technique, a central body must be able to dictate Raman gain set-points across the spans to ensure that the end OSNR results are met.

Dynamic Adjustments Within the System

The determination of the Raman gain using the above technique will only be effective if the dynamic nature of the transmit amplifier profile and the loss profile can be tracked. Let us first consider changes in the transmit amplifier profile.

a) Changes in P1(λ), the Transmit Amplifier Profile

To properly map the Raman gain profile, information about the up-stream transmit amplifier profile should be continuously fed downstream to the receiving amplifier. A continual spectral profile update strategy would obviously strain an overhead channel usage, so it is proposed that only status updates be conveyed on a regular basis from the transmit amplifier. That is, once complete information about the transmit spectral profile has been conveyed to the receiver amplifier, regular message updates can be sent over the overhead channel pertaining to the general operating conditions of the transmit amplifier. A tolerance band would necessarily need to be defined in the transmit amplifier profile in which minor localized changes in its output gain and ripple would not warrant a complete update of its spectral content information to the receiving amplifier. Only under changes causing an "event" in the transmit amplifier's output operating profile would a complete profile update be sent (event = profile change outside of the tolerance band, wavelength additions, loss of wavelengths ...).

If congestion of the overhead channel momentarily detains communication of complete spectral updates from the transmit amplifier, then a method could be put in place to convey only basic information across the overhead channel (such as wavelength x has been added with power y). Short term reliance on the open loop Raman amplifier model

equations (resident with the Raman circuit pack) would be permitted to make limited independent adjustments to the Raman pumps in order to accommodate transmitted profile changes. Closed loop corrective measures may be implemented when the complete up-stream information can be conveyed across the overhead channel.

b) Fiber loss profile: L2 (λ) needs to be dynamic

There should be concern over any Raman gain derivation technique that treats the fiber loss profile as a static entity. Under such conditions, any degradation to the passive elements in the system (such as due to temperature variations) would result in false estimates of the Raman gain. Therefore, whether the fiber loss profile is initially procured through measurement techniques, or estimated based on typical fiber characteristics, this profile information will need to be dynamic, being updated periodically based on receiving amplifier OSA measurements.

So, how can we determine if changes have occurred within the span profile? The answer lies again in knowledge of conditions in the rest of the span. Input spectral profile information can be measured at the receiving amplifier. If this input profile, P4, changes, but it is known that the booster output profile, P1, has remained consistent, and output power monitor conditions remain unchanged on the Raman circuit packs (total power as well as individual pump powers), then the changes can be inferred to have occurred along the transmission medium. The determination of this change is described below.

c) Error in determination of the Loss Profile and the Raman Gain Profile.

The errors in the loss and gain profiles can be remedied as outlined below.

1) Correction of Gain Profile During Initial System Set-Up: In initially setting up a span, there must be a preliminary understanding of system parameters in order to determine the amount of Raman gain required. Knowing the output of the transmit amplifier, P1, knowing what is the desired profile at the receiving amplifier input, P4, and having an initial condition profile for the span loss, L2, one can choose a desired Raman gain profile. A model is used to set the Raman pump powers to achieve the desired Raman gain profile, and the consequential the measured gain will be:

   $$G3measured(\lambda) = P4measured(\lambda) - P1known(\lambda) + L2initial(\lambda).$$

   This may differ from the desired profile due to model errors for the Raman gain. Hence, initial offset adjustments can be made to the pump powers to achieve:

   $$G3measured(\lambda) = G3desired(\lambda) = P4desired(\lambda) - P1known(\lambda) + L2initial(\lambda)$$

   Note in the above argument that the loss profile is assumed to be correct (due to measurement or due to inferred profile based on typical fiber characteristics). This is a necessary starting point.

2) Correction of the Loss Profile in service, when active parameters have not changed:

With any intended modification to the Raman gain profile, it must be assumed that the fiber loss profile is correct and static. This infers that under steady state transmit amplifier and Raman amplifier operating conditions the loss profile must be monitored and updated accordingly to account for environmental impacts upon it.

A change in the loss profile will be noticed as a change of the profile incident upon the receiving amplifier. Under conditions wherein P1 has not changed and the Raman pumps are kept at a given operating point, changes in P4 may be attributed to a change in the loss of the transmission fiber L2. However, a change in L2 will result in a change in G3 through the reduction of the effective length of the Distributed Raman amplifier. Before the change in fiber loss:

$$P4(\lambda) = P1(\lambda) + G3(\lambda) - L2(\lambda)$$

After the small change Δ in the received power at P4:

$$P4(\lambda) + \Delta(\lambda) = P1(\lambda) + G3(\lambda) - \delta_G(\lambda) - L2(\lambda) - \delta_L(\lambda)$$

Where $\delta_G(\lambda)$ is the change in the Raman gain profile and $\delta_L(\lambda)$ is the change in the fiber loss spectrum and is much smaller that $L2(\lambda)$.

As an initial supposition, let's consider $\delta_G(\lambda)$ as being very small compared to $\delta_L(\lambda)$. In such a way, $\delta_L(\lambda)$ can be calculated very easily ($\Delta_{measured}(\lambda) = \delta_L(\lambda)$) since the entire change in $P4(\lambda)$ is attributed to a change in the loss profile. If the assumption that the change in fiber loss is equally distributed all along the transmission fiber, a change in the loss per unit length ($\Delta\alpha$) can be derived from $\delta_L(\lambda)$.

As a second step in the analysis, it is then desirable to estimate the change in Raman gain occurring from the change in the fiber loss, since (as a counter to the initial supposition) there does exist a finite change to $\delta_G(\lambda)$. In the linear regime, the Raman amplification depends only on three parameters: the Raman gain coefficient (Cr), the pumping power (P) and the absorption per unit length at the pumping wavelength (α). In fact, it can be found that for a particular pump(i):

$$\delta_{G,i} = \frac{4.343 \cdot C_{r,i} \cdot P_i \cdot \Delta\alpha}{\alpha_i^{\,2}}$$

Cr and P are constants in the present case, α is known from the previous iteration while $\Delta\alpha$ has been estimated previously. For a given signal wavelength, δ_G can then be estimated by adding the contribution from each pump.

The $\delta_L(\lambda)$ parameter can then be re-estimated by subtracting $\delta_G(\lambda)$ from the measured value $\Delta(\lambda)$:

$$\begin{aligned} L2(\lambda)\text{updated} &= L2(\lambda)\text{previous} + \delta_L(\lambda) \\ &= L2(\lambda)\text{previous} + [\, \Delta(\lambda) - \delta_G(\lambda) \,] \end{aligned}$$

Since it is the desire to maintain a time-invariant profile into the receiving amplifier, loss profile updates infer a need for Raman gain profile updates, as the Raman gain profile set-point is a function of the loss profile. Once adjustments to the Raman pump powers have been made to account for changes to the loss profile, the resultant gain profile measurement can be made,

$$G3measured(\lambda) = P4desired(\lambda) - P1known(\lambda) + L2updated(\lambda)$$

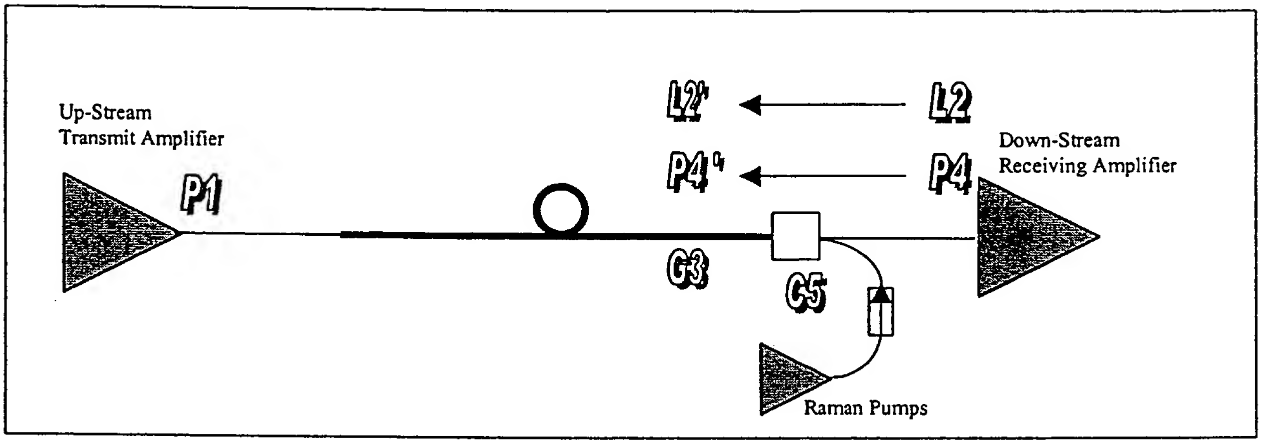
and corrective offset adjustments can be applied to the Raman pumps.

Updates to the loss profile and Raman Gain profile must be made regularly in incremental iterative steps.

3) Static Losses at Receiving End: Effect on calculation of G3

In calculating the Raman gain, it is important to know if the passive losses at the receiving end (i.e. patch panel loss, filter losses...) factor into the equation. If so, there is the potential for a large unknown offset on the measured gain. Consider the diagram below.

Passive Losses at the Receiving End



The figure above is a modification of the concepts presented in earlier. Here an extra element C5 has been added to account for the static passive losses that will appear at the receiving end. Two other parameters appear as well: L2' and P4'. The profile at the receiving amplifier input, P4, is measured after the static losses, C5. The equivalent profile measurement without static losses is P4'. Since loss profile measurements, L2, will also be made at the input to the dual amplifier, the loss due to the fiber alone (without C5) is noted in the diagram as L2'. Raman gain, G3, needs to be defined as the actual gain derived by pumping the fiber. Hence, when setting up pump powers to deliver fiber gain, one must account for the additional static loss C5 (relatively easy to do with closed loop gain control).

Having defined parameters above, consider how the Raman gain is derived.

$G3(\lambda) = P4(\lambda) - P1(\lambda) + L2(\lambda)$, with P4 and L2 measured at the dual amplifier input.

But $L2(\lambda) = L2'(\lambda) + C5$, and $P4(\lambda) = P4'(\lambda) - C5$

Thus:

$$\begin{aligned} G3(\lambda) &= P4'(\lambda) + C5 - P1(\lambda) + L2'(\lambda) - C5 \\ &= P4'(\lambda) - P1(\lambda) + L2'(\lambda) \end{aligned}$$

That is, the calculation of G3 using measured parameters L2 and P4 is insensitive to the static losses on the receiving side.

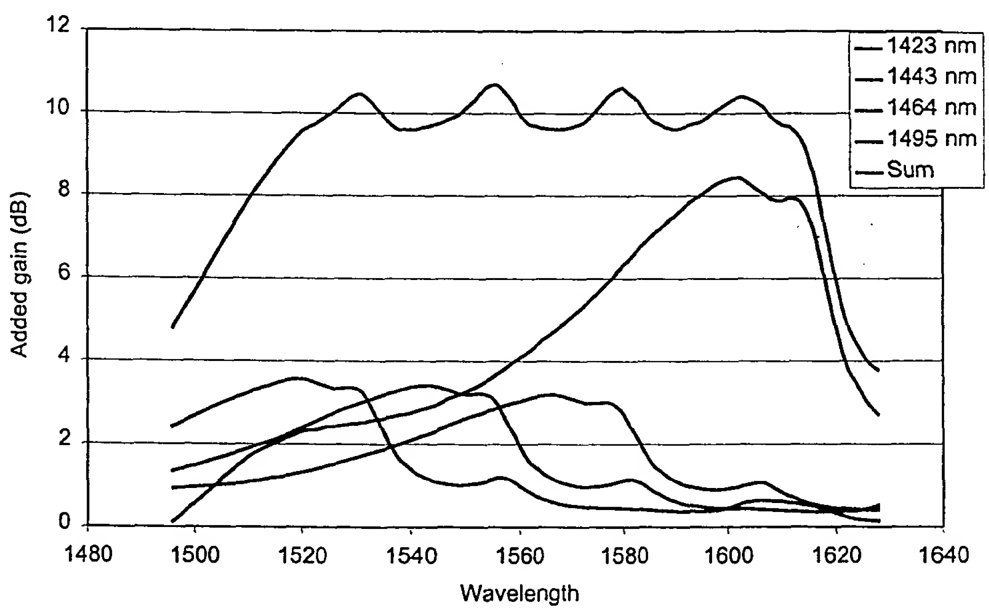
Loss Profile Derivation: Start of Life Step A

Raman pump power settings need to be calculated relative to the fiber loss profile in order to achieve a specified Raman gain profile. For this reason, the fiber loss profile needs to be measured.

Measurement of the loss profile can be effected under start of life, non-traffic-carrying conditions. If the transmit amplifier pumps are turned up to deliver superfluous (high power) ASE, this launched ASE profile could first be measured at the amplifier output using the OSA, and then measured at the receiving dual amplifier input. The difference between the profiles would be the mapping of the span loss profile.

Derivation of Single Pump Raman Gain Profile: Start of Life Step B

The combined Raman flat gain profile is the result of the superposition of several individual pump wavelength profiles, as illustrated in an example below.



It is evident from this diagram that the shapes of the pump profiles must be known to permit an effective superposition. The shape is empirically determined, and is dependent on fiber type.
A caveat lies in the reliability of using a pre-determined per-fiber-type typical Raman pump profile when implementing a solution. This allows for no tolerance variations with same-type fibers. The work around to this problem is in measuring the pump profile on site. Under the same start of life (traffic free) conditions used in determining the loss profile, one can turn up each pump wavelength independently, and map the resultant

profile at the receiving amplifier. The resultant profile is derived through the difference between the ASE profile incident on the receiver amplifier before and after the Raman pump power application. This technique would be particularly valuable in a situation wherein a foreign fiber type has previously been spliced into a span, and the typical profile for the dominant fiber type may not be applicable.

Initial Raman Pump Offsets: Start of Life Step C

It was mentioned earlier (in "Correction of Gain Profile During Initial System Set-Up") that during system initialization, the Raman gain model will provide pump set-points which may be non-optimal due to model inaccuracies. That is, the resulting gain profile will be measured through

$$G3measured(\lambda) = P4measured(\lambda) - P1known(\lambda) + L2initial(\lambda),$$

and this measured profile may not match the desired profile. Pump offsets may be necessary to achieve:

$$G3measured(\lambda) = G3desired(\lambda)$$

As a third step in the start of life initialization procedure, it is possible to provide an initial estimate of this offset, to provide a first order of correction to the model before traffic is activated onto the link.
Under the transmitter amplifier ASE condition, if the Raman pumps were then activated to provide a pre-determined (modeled) gain, that resultant gain could be measured at the receiving amplifier. This provides a method for comparing the gain provided by the model against empirical observation.

To further on this, if a link budget analysis has dictated that the Raman gain within a span is to have a value Y, two other gain values can be measured using the above procedure, X being a value marginally below the desired point, and Z being a value marginally above the desired point. The error between the set-point gain X and measured results can be obtained. Likewise, the error between the set-point gain Z and measured results can be obtained. From interpolation between these error results, a linear function on the expected error in the gain Y can be found and used to first provide initial pump offsets on the model, and then for adjustment purposes.